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What is the global potential for renewable energy?

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ABSTRACT

World energy demand is projected to rise to 1000 EJ (EJ = 10^{18} J) or more by 2050 if economic growth continues its course of recent decades. Both reserve depletion and greenhouse gas emissions will necessitate a major shift from fossil fuels as the dominant energy source. Since nuclear power is now unlikely to increase its present modest share, renewable energy (RE) will have to provide for most energy in the future. This paper addresses the questions of what energy levels RE can eventually provide, and in what time frame. We find that when the energy costs of energy are considered, it is unlikely that RE can provide anywhere near a 1000 EJ by 2050. We further show that the overall technical potential for RE will fall if climate change continues. We conclude that the global shift to RE will have to be accompanied by large reductions in overall energy use for environmental sustainability.

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1. Introduction: world energy projections

Global primary energy consumption from all sources in 2008 was 514 EJ (EJ = exajoule = 10^{18} J), with over 80% being from fossil fuels [1]. What is energy use likely to be in the years 2030, 2050 or even 2100? Various organisations such as the oil companies BP and Shell, the US Energy Information Administration (EIA), the European Commission (EC), the International Energy Agency (IEA), the International Atomic Energy Agency (IAEA), the International Institute for Applied Systems Analysis (IIASA) and the World Energy Council (WEC) have all projected values for one or more of these future dates [2–9]. The lowest and highest values for projected primary energy use from each of these organisations are shown in Table 1. There is remarkably little spread of values either within or between the various projections up to 2050. By 2050, world energy use is forecast to rise to 800 EJ or more, and the one projection for 2100 envisages that levels as high as 1740 EJ could occur.

The last entry in the table shows the estimates by the Tellus Institute [10]. This organisation included in its scenarios a transformational one in which economic growth was no longer a key aim of economies. Although the upper values for energy use in each year are similar to the other upper values in Table 1 (reflecting business-as-usual scenario variants), the lower values are very

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Table 1
Global primary energy projections, 2020–2100, in EJ.

Organisation and year	2020	2030	2050	2100
BP (2011) [2]	565–635	600–760	NA	NA
EC (2006) [5]	570–610	650–705	820–935	NA
EIA (2010) [4]	600–645	675–780	NA	NA
IAEA (2009) [7]	585–650	670–815	NA	NA
IEA (2010) [6]	NA	605–705	NA	NA
IIASA (2007) [8]	555–630	NA	800–1175	985–1740
Shell International (2008) [3]	630–650	690–735	770–880	NA
WEC (2008) [9]	615–675	700–845	845–1150	NA
Tellus Institute (2010) [10]	504–644	489–793	425–1003	243–1200

different, particularly after 2020, where they progressively fall to 243 EJ by 2010. The 2100 value is less than a quarter of the IIASA's minimum scenario value for 2100. Much of this lower energy consumption in 2100 is a result of a far lower global GDP than in the Tellus high energy scenario, but like the energy projections of other organisations, energy intensity is also expected to fall. Such low energy use would delay fossil fuel depletion, adding plausibility to the scenario.

Another approach to projecting energy demand is to ask what future energy demand levels would occur if the entire world achieved present OECD levels of per capita energy consumption. At present, energy and electricity consumption values, and CO_2 emissions from fossil fuels, all on a per capita basis, vary greatly from country to country, as shown in Table 2. Electricity use is far more polarised than primary energy, since the latter figures include non-commercial fuel wood, which accounts for most energy use in very low income countries. Assume that the global 2050 population is 9.15 billion, the median UN [11] estimate. If all have the same per capita energy use as the 2008 OECD average, (and per capita use in the OECD appears to have stabilised) global energy consumption would be 1748 EJ, much higher than the projections given in Table 1 for 2050. If the present US per capita level of 314 GJ (GJ = gigajoule = 10^9 J) was the standard for energy consumption, the figure would rise to 2873 EJ.

Yet another approach has been proposed—the 2 kW society [12]. Spreng argued that a continuous power of 2 kW (63 GJ/capita/year) for everyone would be sufficient to provide all with a high quality of life, compared with the 2008 level of 77 GJ/capita (Table 2). By the year 2050, 63 GJ for all would require 577 EJ annually, not much above the present level, but the total would further increase as long as global population continued to rise. Of course 2 kW for all would mean cuts in the present OECD level from 191 GJ to 63 GJ. In summary, in the 'business-as-usual' future assumed by all the organisations (except Tellus) listed in Table 1, we will need roughly 600–800 EJ by 2030, and up to 1000 EJ by 2050. Energy consumption equality at 2008 OECD levels by 2050 would need about 1750 EJ, but global energy equality at 2 kW would only need a third of this level.

Table 2
Energy use and emissions per capita in 2008, various countries.

Country	Primary energy use (GJ/capita)	Electricity use (kWh/capita)	Fossil fuel CO_2 (t/capita)
Qatar	788	15,680	42.09
Iceland	690	49,818	6.89
UAE	546	16,895	32.77
Luxembourg	353	15,883	21.27
USA	314	13,647	18.38
China	67	2453	4.91
Tanzania	19	84	0.14
Ethopia	16	42	0.08
Haiti	12	23	0.24
Eritrea	6	48	0.09
OECD average	191	8486	10.61
World average	77	2782	4.39

Source: [6].

2. Estimates for technical potential of renewable energy

The previous section demonstrated that world energy demand in 2050 could be in the range 800–1000 EJ in a business-as-usual world, assuming steady growth in the global economy. The obvious question arises: how is this energy demand to be met? Like today, it must come from some mix of fossil, renewable and nuclear energy sources, but the mix may be very different from today's.

The present heavy emphasis on fossil fuels will have to change, even though all except the last projection in Table 1 assume its continuance as the major energy source. Fossil fuels cannot continue to dominate energy provision for more than a couple of decades, for two reasons. First, it is likely that reserves of easily extracted oil, gas and even coal will all have peaked by 2030 [13–17]. The peak in output will not only be determined by geological depletion, but also by national resource politics. Energy exporting countries could in future restrict outputs to gain political leverage, or to extend the life of their reserves in order to either provide future export earnings or for their own energy security [14].

Second, fossil fuels are responsible for an estimated 74% of all CO_2 emissions [18]. Global atmospheric levels are now at 390 ppm, and some Earth scientists have argued that this level is already too high, and should be reduced to 350 ppm [19,20], mainly to prevent irreversible loss of the Greenland ice cap. Any move to unconventional fossil fuel sources, such as the Canadian oil sands, deep ocean oil or shale gas will significantly increase the monetary, environmental and greenhouse gas costs per unit of delivered energy [14]. Proposed solutions for countering the climate impacts of fossil fuel emissions include CO_2 capture from large fossil fuel combustion plants, and even direct CO_2 capture from the air, followed by sequestration, and geoengineering. All face serious problems, such as progressive ocean acidification for geoengineering [14], and neither would address fossil fuel depletion.

Nuclear energy has been proposed as a solution to the twin challenges that face fossil fuels. But even organisations favourable to nuclear development, such as the IAEA [7], did not envisage nuclear energy increasing its share much beyond its present 5.8%, even in scenarios most favourable to nuclear power (and before the accidents at the Fukushima Daiichi reactors in March 2011). These forecasts are consistent with the stagnation in the nuclear share of total energy supply over the past decade [1]. This stagnation is the result of the high costs and long lead times for nuclear plant construction, and widespread political opposition to nuclear power, which is unlikely to wane as long as the reactor safety, waste disposal and nuclear proliferation problems remain unsolved [14].

The earthquake and tsunami that struck Japan on the 11th March 2011 will further reduce future nuclear power generation [21]. Apart from the electricity generation lost from the irreparably damaged reactors, other reactors in Japan are likely to experience prolonged shutdowns to install safety upgrades. Japan has already scrapped plans for 14 new reactors [22]. Ageing reactors in both Europe and North America might also be at least temporarily closed, and, lifetime extensions for older plants are now less likely to be approved.

If CO_2 levels are already too high and nuclear energy can at best be only a minor contributor to the future energy mix, then the various forms of renewable energy (RE) will have to provide for the bulk of future energy needs. But not only must we attempt to answer the

question of whether RE can meet nearly all future energy demands, but also what the timetable for the transition from fossil fuels to RE might feasibly look like.

Table 3 shows how various energy researchers have answered the first question. It shows the technical potential for the six main groupings for renewable energy. Only some very minor possible RE sources, such as the osmotic pressure transition between freshwater and seawater, have been omitted. The ocean energy category includes tidal, ocean current, and wave energy as well as ocean thermal energy conversion. The technical potentials for solar, wind, hydro and ocean energy are given as the gross output of electricity possible. For biomass, the values refer to the primary energy of the biomass before any conversion; for geothermal energy, electricity and the vastly larger low temperature direct heat potentials have been listed separately. The only important omitted category is passive solar energy, which can be difficult to separate from energy efficiency measures.

Ideally, technical potential values should exclude possible locations with incompatible land uses [14,23,24]. However, these exclusions, if considered at all, have not been consistently applied across all RE sources. Particularly for hydro energy, sizeable settlements and even large cities have been demolished to make way for hydro reservoirs, mainly in industrialising countries. And as we show below, determining which areas to exclude for RE, especially biomass, is very difficult. Some of the studies in Table 3 also give RE economic potentials, which can be defined as that part of the technical potential which is economically feasible given the costs for competing energy sources [24]. Some of the upper values listed can be quickly ruled out. For biomass, 1500 EJ is 79% of the terrestrial NPP, and is in addition to other major human uses of biomass. The highest geothermal value is two orders of magnitude larger than the annual replenishment rate, suggesting this rate of extraction could not be sustained for long.

All RE capture devices require inputs of energy in order to generate an energy output. Using wind energy as an example, energy inputs are needed to manufacture the turbine and its support structure, for building support infrastructure (access roads, transmission lines), for operation and maintenance, and finally for decommissioning and removal of the turbine. The ratio of gross energy output to energy inputs, (both measured in common energy units, usually primary energy) we call the energy ratio. *Net* energy is gross energy output less input energy; it is net energy which fuels the non-energy sectors of the economy.

Table 3 shows that for all six forms of RE listed, except hydropower, published estimates span an enormous range. Upper and lower published values can vary by one and sometimes two orders of magnitude (or even more for geothermal energy). This range raises serious questions about the usefulness of technical potential figures. One problem is that these estimates are not usually based on calculations of energy ratios. For an RE source to be viable, an energy ratio of at least one, and probably much higher, perhaps five, is needed [34], although this requirement can be relaxed during the development stages for a new RE source. If this criterion was applied, the upper values of the estimates would probably be far lower. More importantly, published values of technical potential unwittingly give the false impression that the first and last EJ of technical potential for a given RE source have similar costs and net energy.

3. Energy ratios for RE will fall as annual output rises

In this section we examine why the energy ratio for each RE source, whether considered at either regional or global scales, will decline as annual output rises. We will mainly do so on general grounds, as very few researchers have tried to document how energy ratio varies with output, except for wind energy. For wind energy, however, several researchers have assessed the energy ratio decline at both local and global levels; accordingly, quantitative analysis is possible for wind energy. But before doing so, we will first need to examine how calculated energy ratios vary even for a given RE device in a given setting.

Energy researchers have used two main methods for calculating input energy costs. Process analysis is a bottom-up approach that looks at the materials embodied in a wind turbine and its tower, for example, and calculates the energy cost of their manufacture. The energy costs for site assembly are calculated from the fuel used for equipment such as bulldozers, and so on. The input–output method is based on the detailed input–output analyses of national economies. The hybrid method combines both approaches, using the input–output approach to capture energy costs usually ignored by process analysis, such as the energy costs of supporting goods and services. The calculated energy ratios can be very different for the different approaches. Using hybrid analysis, Crawford [35] showed that the energy ratio for a given wind turbine is much smaller than calculated by process analysis. Zhai and Williams [36] also found much lower hybrid analysis energy ratios than those usually calculated, this time for photovoltaic (PV) systems.

3.1. Wind energy potential and energy ratio

Lenzen and Munksgaard [37] in their comprehensive analysis of the energy analyses in the literature for wind turbines noted the importance of the capacity factor, which is a proxy for average wind speed. The importance of capacity factor was further illustrated by Honnery and Moriarty [38], who showed that as global wind energy production increased, the marginal capacity factor of wind turbines decreased, while Hoogwijk and colleagues [23] using wind energy costs (cents/kWh), demonstrated a similar result.

A more explicit relationship between energy ratio (E_r) and global wind energy potential can be obtained by combining the wind energy production data from Honnery and Moriarty [38] with the input energy data from their 2011 paper [39] which is derived from Crawford [35]. In this estimate, wind energy potential, expressed as annual gross electrical energy output, is obtained by placing a 2 MW wind turbine per square kilometer of available global land surface. Output electrical power is determined via a calculation based on local wind speeds and land surface conditions for each turbine. Input energy per turbine accounts for both turbine production and operation over a typical 20 year life time.

The result is shown in Fig. 1 for two different land coverage cases. In the unconstrained case, all land area is considered; in the land constrained case, similar to [23], sensitive areas such as forests and wetlands, as well urban areas, irrigated cropland and pasture are removed. Removing these areas has the effect of reducing the gross amount of energy produced. For both cases, annual energy power output is shown as a distribution in energy ratio and as a cumulative sum of the distribution with the summation occurring from highest to lowest energy ratio.

In the figure, the reduction in energy ratio with increasing annual gross wind energy output is clearly evident; in both cases, around half the output occurs for a marginal energy ratio of around $E_r = 8$, with greater sensitivity at higher energy ratios because of the limited number of locations with high average wind speeds. Although there is a slight bias away from higher energy ratios with implementation of the land constraints, the reduction in output that occurs is distributed uniformly.

In the data presented in Fig. 1, turbine input energy is independent of local conditions; a constant value per turbine is used. Among the many factors which could alter this are the distance the turbine array is to the nearest high voltage grid, the distance to the nearest population centre, the available infrastructure (e.g. roads,

Table 3
Published estimates for RE global technical potential.

Study and year of estimate	Solar	Wind	Ocean	Hydro	Biomass	Geothermal	
						Electricity	Heat
Hafele (1981) (‘*realizable*’ *potential*)	NA	95 (*32*)	33 (*16*)	95 (*47*)	189 (*161*)	3.2 (*3.2*)	47 (*16*)
Lightfoot/Green (2002) (*range of values*)	163 (*118–206*)	72 (*48–72*)	0 (*1.8–3.6*)	19 (*16–19*)	539 (*373–772*)	1.5 (*1.5*)	NA (*NA*)
Gross et al. (2003)	43–144	72–144[a]	7–14[b]	NA	29–90	NA	14–144[c]
Sims et al. (2007)	1650	600	7	62	250	NA	5000[c]
Field et al. (2008)	NA	NA	NA	NA	27	NA	NA
Resch et al. (2008)	1600	600	NA	50	250	NA	5000[c]
Klimenko et al. (2009) (‘*economic*’ *potential*)	2592 (*19*)	191 (*8.6*)	22 (*2.2*)	54 (*29*)	NA (*NA*)	22 (*3.6*)	NA (*NA*)
Cho (2010)	>1577	631	NA	50	284	NA	120
Tomabechi (2010)[d]	1600	700	11	59	200	NA	310,000[c]
WEC (2010)	NA	NA	7.6[b]	57.4	50–1500	1.1–4.4	140
All studies range	118–2592	48–600	1.8–33	50–95	27–1500	1.1–22	14–310,000
Earth energy flows	3,900,000	28,400	700	130–160	3000	1300	

Source: [14,18,25–33].
NA: not available.
[a] Onshore only.
[b] Wave only.
[c] Includes both electricity and direct heat.
[d] ‘Usable maximum’.

water, etc.) and terrain complexity. While it is possible to correlate these factors with, for example, local average wind speed, global wind energy studies are yet to attempt this.

Some insight into the potential importance of local conditions on system input energy can be gained by looking at the global distribution of wind energy potential. Around 50% of global wind energy occurs in just 5 countries (USA, Russia, Canada, Australia and Argentina) [38]. Yet, these countries account for only around 10% of the global population, and about 20% of total land surface area. Redistributing energy from energy rich to energy poor regions will result in higher energy inputs as grids are extended or energy is converted to other sources (e.g. hydrogen) for export. It will also result in reduced net energy output through higher system losses (e.g. transmission and voltage conversion). These factors will act to shift global potential to lower energy ratios than indicated in Fig. 1.

3.2. Other RE sources

Given the often unique relationship between an RE resource and its energy transformation technology, each RE system will have its own input energy sensitivity. As an example, for Hot Dry Rock geothermal electricity, Herendeen and Plant [40] observed that ‘the energy ratio is strongly dependent on the size of the fracture produced’. Their data also showed that the energy ratio increased as the thermal gradient rose from 35 °C/km to 55 °C/km. Conversely, the energy ratio will fall as high thermal gradient fields are preferentially developed, and progressively deeper heat sources must be exploited.

Bioenergy is only one of the many uses for biomass; we also use biomass for food crops, for animal forage, for natural fibres (e.g. cotton, flax), and for forestry products, both for construction and for the paper and pulp industries. Some sources for bioenergy are fortunately complementary to other biomass uses, such as crop and forest residues surplus to those needed for maintaining soil fertility and preventing erosion. Use of other sources, such as feedlot effluent wastes, or municipal, sawmill or sugar cane wastes, can help solve waste disposal problems. Using sewage gas or landfill gas can reduce emissions of methane, a potent greenhouse gas, to the atmosphere [41]. The energy ratio for these bioenergy fuels can be very favourable, because of low ascribed input energy costs.

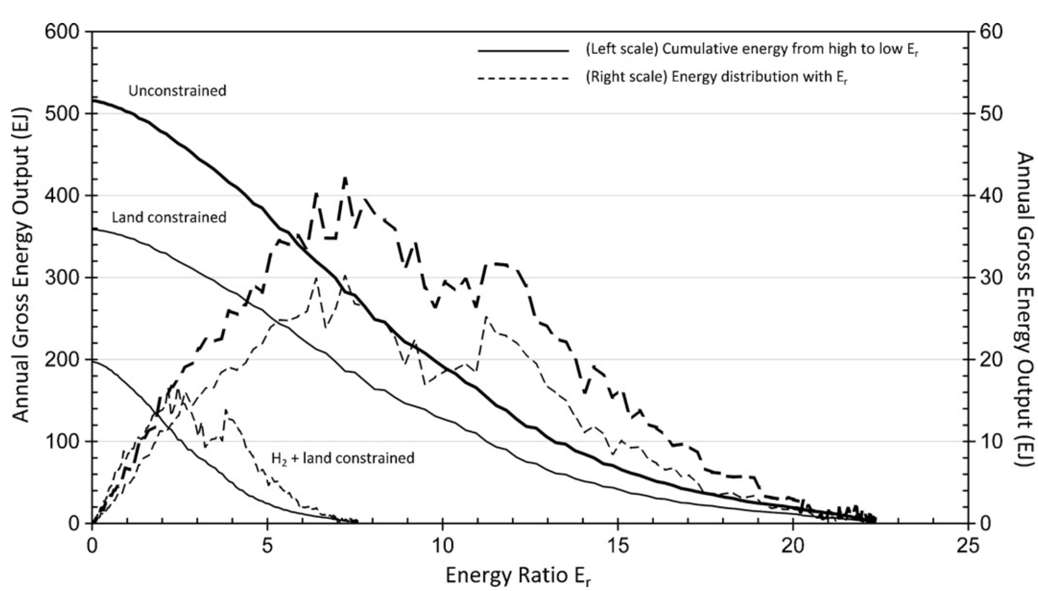


Fig. 1. Global annual gross wind energy output against energy ratio (E_r). Energy is shown as both a cumulative sum for the marginal E_r (left axis) and distribution in E_r (right axis). See text for explanation of the three cases shown in the figure.

But these sources can only provide a limited amount of bioenergy, even if locally important [41]. They may even decrease in future: municipal wastes if packaging is decreased or organic wastes are recycled; crop and forestry wastes if increasing soil erosion risk (see Section 5.1) necessitates that more of these wastes are left in place. For large quantities of bioenergy, plantations will be needed. But, as we have shown elsewhere [41], the energy ratio for such fuels will be far lower than for true biomass wastes.

Ocean thermal energy conversion (OTEC) could produce constant power output—at least for small islands. But for major energy output from OTEC, the units would need to be ship-mounted and move over tropical oceans, in order to maintain surface vs. depth temperature differences. A cable link to shore would no longer be possible, and, the electricity would need to be converted and stored on board for later delivery to shore [34]. Larger amounts of OTEC energy would thus only be available at declining energy ratios.

Over two decades ago, Baines [42] analysed New Zealand hydro projects and found that the energy ratio was lower for newer projects and predicted that for future projects the ratio would continue to fall. This is in accord with the view of Pritchard [43], that the world has fewer and fewer good sites left for hydro dam development. Different hydro projects will differ in terms of surface area of the impounded reservoir per EJ of electricity generated annually [44], and also in terms of cubic metres of dam wall material per annual energy output; both factors are important for the energy ratio.

Global solar energy potential is so vast that it might seem that any significant decline in energy ratio would occur at energy levels well beyond those of human interest. After all, the world's hot deserts are tens of millions of km^2 in extent, with low populations. Every one million km^2 of the Sahara (assuming an average annual insolation of 2300 kWh/m^2) would have an annual solar energy input of 8280 EJ. At 50% coverage by collector surface and 10% conversion efficiency, electrical output would be 414 EJ per million km^2. These arid, largely cloudless regions would be seemingly well-suited for Solar Thermal Energy Conversion (STEC) plants. However, the vast areas of the Sahara covered with moving sand (dune fields) cannot be used for PV or STEC farms; instead, the more surface-stable semi-arid regions will be favoured. These areas have some vegetation—and inhabitants.

These deserts of North Africa are part of the ambitious Desertec plan to supply 15% of European electricity demand by 2050, at a cost estimated in 2009 at 400 billion Euros [45]. However, while 15% of electricity from STEC plants might be accommodated in a greatly extended and strengthened European grid, the intermittent RE sources, wind, solar, and perhaps ocean energy may have to supply most of the world's energy needs, both electric and non-electric. It will therefore prove necessary to convert most intermittent electricity into an energy form that can be stored and transported, probably hydrogen [38]. But such a need for conversion and storage could reduce net energy output by up to half, with a corresponding fall in energy ratio. Even though some storage is possible with STEC systems, the world's cloudless desert regions lie mainly in sub-tropical, not equatorial, regions. But at 35° N (the latitude of the initial STEC plants in California) or 35° S, winter insolation is only about half that of the level in summer. Attempting to provide for peak winter energy demands in central Europe with only a few days of energy storage in molten salts would necessitate very high capacity levels, with correspondingly high energy input costs, and lower system energy ratios.

3.3. Discussion

It is inevitable as RE progressively dominates energy supply, that energy ratios for intermittent sources will fall as energy conversion and storage becomes necessary to balance energy production with demand. To illustrate this for wind, one possible method of storing the electrical energy produced is to convert it to hydrogen via hydrolysis of water. The effect of this is shown in Fig. 1 for the annual energy produced under the land constrained case. Conversion to hydrogen is achieved at an estimated system efficiency of 55% [38], where output is the gross heating energy of the annual hydrogen production. The additional input energy required to undertake this conversion [39], combined with the reduced energy output gives rise to a significant reduction in energy ratio for this system with all energy output occurring for $E_r < 7.5$, and 50% for $E_r < 2.5$.

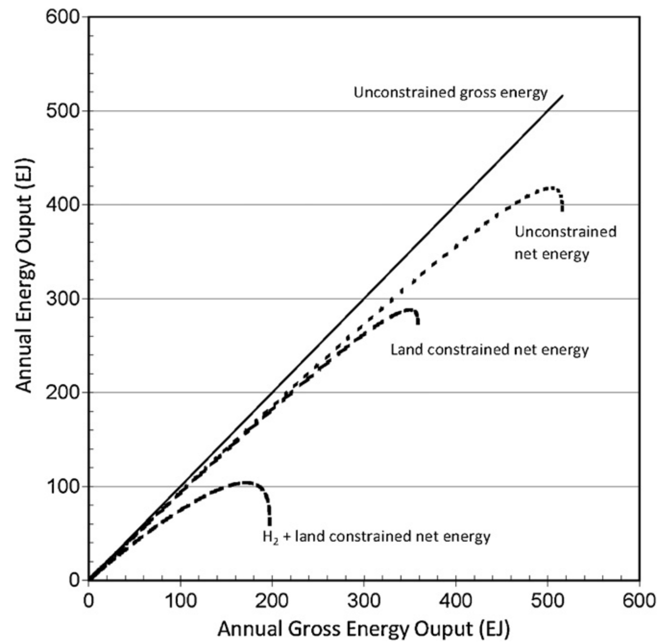


Fig. 2. Annual net wind energy output against gross annual wind energy output for the data of Fig. 1. See text for details.

Coincident with the decline in energy ratio is a reduction in net energy output as RE system complexity increases. This is shown in Fig. 2 for the wind data of Fig. 1. In this figure, annual net energy output (gross less input energy) is seen to increase with gross energy output until a peak value is reached corresponding to $E_r = 1$, after which net output falls: additional wind turbines produce less energy than used in their production and operation. As anticipated, both peak net energy and its corresponding gross output value are seen to depend on technology and resource availability and although not shown, a peak in net output is expected to occur for each of the other RE sources examined here [46].

Clearly, it matters greatly whether or not the peak energy value from all sources, but mainly wind and solar, occurs in the range of human interest; as shown in Section 1, this could be as high as 2000 EJ in a business-as-usual world. Further, as will be discussed in Sections 4 and 5 below, it is likely that the peak RE value will fall once additional constraints imposed by the environment and climate change are considered.

Opposing declines in energy ratio will be improvements in technology, and cost reductions through learning as output of RE grows (although as Yeh and Rubin [47] have shown, reliance on simple log-linear curves for predicting lower future energy technology costs is misplaced). Mature RE technologies like hydroelectricity and wind can expect few further improvements, but for others, like PV cells, further technological breakthroughs and cost reductions with increased production are possible, or even likely. However, as experience with fossil fuel systems has shown, benefits from technological improvements can often only be attained once the

operating life of existing plant has been reached; timing is therefore critical.

A final factor to consider is the availability of the materials used to produce RE systems. A number of the most rapidly advancing RE technologies depend on materials that are potentially in short supply, or which will require increasing amounts of energy input to extract and process raw materials as resource quality falls. The cost reductions implied by learning curves depend on exponential growth in production, but such growth will also hasten resource depletion if RE sources are to replace fossil fuels in the future [14]. Several researchers, including Fridley [48] and Kleijn and van der Voet [49], have documented how some amorphous PV cells, permanent magnets in wind turbines, as well as several other 'green technologies' such as fuel cells, rely on mineral resources that may not be sufficient to satisfy the orders of magnitude increases needed for these technologies.

4. Technical potential depends on the level of environmental constraints

Environmental effects from RE can occur at the very local level, and for low levels of output from the RE source. For example, one wind turbine can cause some bird or bat deaths. But as the global output from a given RE source increases to (say) several hundred EJ, global environmental effects can occur, such as possible changes to precipitation or heat fluxes in the case of wind energy [50].

In future, as RE comes to dominate the total primary energy supply, constraints on RE projects will be subject to two conflicting forces. On the one hand, as new sources like wind and solar energy are scaled up by several orders of magnitude from their present low levels, novel environmental problems are likely to surface which will tend to constrain RE energy growth. Much research has stressed the environmental consequences of hydropower [51–53] even though its output is today only around 12 EJ and will likely never be more than 20–30 EJ. In contrast to wind and especially solar, we now know a lot about the effects of large-scale hydro systems; we can thus get some insight into what problems a scaling-up of these energy sources might throw up.

Boyles et al. [54] have shown that for wind power, environmental concern is not just an abstract principle. They estimate that insectivorous bats, by suppressing populations of insect pests, are worth nearly four billion dollars to the US economy alone. Although bird and bat deaths have been stressed, other more subtle adverse effects on wildlife, such as habitat fragmentation due to access roads, could also be important [55]. Simon [56] has discussed the constraints on wind and solar energy projects in the US, including Native American objections to the siting of a solar plant in the South-West. Dean [57] has even hypothesised that the mechanical vibrations from proposed wind farms on peat soils in Scotland could destroy these unique soil ecosystems by changing their aeration and hydrology.

Boehlert and Gill [58] point out that for ocean energy, including off-shore wind farms, the effect on marine mammals is unknown, but could be a 'show stopper'. In the IPCC 2007 report, Sims et al. [18] discuss the environmental problems of geothermal energy. These include land subsidence and chemical pollution of waterways, although re-injection of fluids can potentially ameliorate these problems. Table 4 summarises the known and possible environmental and social effects reported in the literature for the six major RE types.

On the other hand, if RE is to take over from fossil fuel energy the task of supplying the world's growing energy needs, it could be argued that it is necessary to cut back on environmental constraints. Otherwise, many of the most suitable sites will not be developed. Two important arguments can be advanced in support of this position. First, by using the best sites (those with the highest energy ratio), the total number of wind turbines, for example, can be reduced for a given net energy output—and electricity costs will be lower. This is a similar to the argument put forward in favour of intensive agriculture, that because of higher yields per hectare it saves destruction of natural forest.

Table 4
Environmental and social effects of RE.

RE type	Environmental and social effects	References
Solar	Pollution from PV production; adverse effects on fragile semi-arid land ecosystems; competition for fresh water; depletion of scarce materials; albedo decreases.	[14,56,59]
Wind	Bird and bat deaths; possible habitat loss for other wildlife; noise and vibration pollution for nearby residents; adverse effects on visual amenity; possible adverse effects on marine mammals from offshore wind farms; possible climate changes for large-scale implementation.	[14,31,54–57,60–63]
Ocean	For OTEC, disruption to marine ecosystems from need to pump vast amounts of seawater; possible adverse effects on marine mammals from wave and current energy devices; shipping disruption.	[14,58,64]
Hydro	Loss of homes and livelihoods for those displaced; fresh-water biodiversity loss; inundation of farmland or natural forest; possible increases in micro-seismicity and slope instability; loss of heritage sites; increased downstream erosion; coastal land retreat and declining soil fertility from loss of sediment deposition; greenhouse gas emissions from submerged biomass.	[14,18,52,53,65]
Biomass	Competition with other biomass uses (especially food production) for fertile land and water; loss of existing uses for biomass wastes; biodiversity loss.	[41,65,66]
Geothermal	Land subsidence; increase in micro-seismicity; potential air and water pollution.	[14,18,63]

Another argument is that we also need to weigh the adverse environmental consequences of major RE installations with those from alternative energy production methods, particularly fossil fuels. While it is true that emissions of SO_x, NO_x and particulates per kWh output have declined because of pollution capture devices, especially in OECD countries, global CO_2 emissions continue unabated. Further, as fossil fuel availability declines, unconventional sources are being increasingly tapped, such as Canadian oil sands, deep sea oil and natural gas shales from shales. These sources not only tend to have higher CO_2 releases per unit of delivered fuel than conventional sources, but have other serious environmental effects, as illustrated by the Deep Horizon oil spill in the Gulf of Mexico. New production methods, such as hydro-fracturing for NG (which involves breaking up the shale formation the NG is trapped in to facilitate gas extraction), and mountaintop mining for coal in the US, also exacerbate water pollution, as well as carbon emissions [67].

The environmental problems of RE operation are thus pitting local environmentalists against major environmental organisations with a more national or even global viewpoint, including awareness of the environmental costs of fossil fuels. This conflict is

already happening in the case of wind generation, but can only become more acute as more environmentally-sensitive sites must be tapped if output is to rise. RE sources, unlike fossil fuels, are regarded as 'clean fuels'; the public thus find it harder to accept environmental damages from these energy sources. Above all, we must realise that there is a third way; we can reduce the environmental problems of both RE and its alternatives by using less energy, either through more efficient energy-consuming devices or less use of these devices [14,68,69].

5. On-going climate change will affect RE technical potential

The Earth is committed to a further 0.7 °C temperature rise even if all emissions stopped, because of the thermal inertia of the oceans, which delays the eventual temperature rise for any constant level of climate forcing. And given the vast investments in fossil fuel infrastructure, it is probable that atmospheric concentrations of greenhouse gases will continue to rise for some time, and with them global temperatures. An important consequence is that the technical potentials for the most important RE sources can be expected to change with this on-going climate change. Only geothermal and tidal energy sources will not be directly affected.

5.1. Hydropower

At the global level, researchers disagree on the impact of climate change on total hydro output. Using the POLES model, Mima and Criqui [70] found rises in global hydro output of 3.7% for 2050 and 6.8% for 2100. Following the study of European hydro by Lehner and colleagues [71], they found declines for Europe, but gains in other world regions. For the Pacific Northwest, the model results of Hamlet et al. [72], showed that by the 2080s, any increases in winter hydro production were more than offset by summer decreases, with overall annual reductions of 2.6–3.2%.

An important consideration here is the long life of hydro projects compared with other RE sources: up to 100 years for large hydropower dams [73]. Hydro planning must in consequence take a much longer view than, for example, wind farm planning, with perhaps a 20 year life. Uncertainty regarding future river flows will inevitably be higher the longer the time frame used. Although in general it is expected that precipitation will rise in a warming world, at the regional and river basin level, different GCMs often give divergent results for change, sometimes with varying sign. Ongoing global warming will also alter the temporal nature of stream flows (because of less precipitation falling as snow in alpine and high latitude regions) and reservoir sedimentation rates (because of greatly increased erosion rates expected from increased extreme rainfall events) [14]. All these factors will add to the uncertainty for future hydropower investment, leading to lower installed capacity.

If the world continues to take no effective climate mitigation actions, it is possible that at some future date one or more nations might decide to try geoengineering. The most likely method is by aerosol injection into the lower stratosphere, as it has low direct implementation costs, will quickly lower temperatures, and can be reversed [14]. Unfortunately, it is not possible to stabilise temperatures without an average reduction in precipitation levels [74], which will reduce hydro potential. On the other hand, the lower resultant temperatures should mean lower reservoir evaporation and fewer extreme precipitation events or droughts, which would both increase potential output and make flows more predictable.

5.2. Bioenergy

Zhao and Running [75] have examined the annual variation of global NPP over the past three decades and concluded that NPP has fallen in the years 2000–2009. They argued that climate change is the main cause. Other research using coupled carbon-climate models [76,77] has shown that carbon stored in terrestrial biomass can be expected to decline in the coming decades if GHG emissions are not halted. Both forests and soils, particularly in the tropics, will then change from being CO_2 sinks to net sources.

As already noted, bioenergy is only one of several competing human uses for biomass. The share of NPP appropriated by humanity – human appropriation of NPP (HANPP) – has been estimated at between 14.1% and 26.1% [78], although values of up to 55% have been reported, depending on which items are included [79]. Some researchers, e.g. [66] regard the present HANPP level as already unsustainable. In any case these values are very high compared with, for example, wind or solar energy utilisation. If meeting the food needs of an expanding world population is seen as a priority, then bioenergy must compete with the other uses of biomass (which are also rising) for the non-food fraction of the sustainable level of HANPP. It follows that future bioenergy production levels will be very sensitive to any factors which could lower NPP.

5.3. Wind energy

The potential for wind energy will be affected by climate change to the extent that average wind speeds change. The literature on this topic differs in estimates of the size and even the sign of the changes. Pryor and Barthelmie [80] found only small reductions in potential European wind output: <3% by 2050 and <5% by 2100. They also stressed that the need for de-icing turbines would decrease. For Brazil, a recent study [81] found that overall wind potential would, if anything, show a small future increase with global climate change.

Sailor and colleagues [82] found that for the Northwest US, the wind power resource by the end of the century would decrease by up to 40% in the summer and spring months, but with no consistent change in the other months. Because of the non-linear dependence of wind power output with wind speeds, the 40% decline resulted from only about a 5–10% fall in wind speeds.

Ren [83] developed a general relationship for China as a whole using eight general circulation models. He found that wind power declined as a power law of temperature change, and that even for the mild IPCC emissions scenario (A1B) a 14% reduction in available wind power could be expected in China by 2100. As he explains: 'The global poleward temperature gradient drives the overall circulation pattern of the earth's atmosphere'. The reduction in wind power is thus caused by the decreased temperature differential between the polar regions and lower latitudes as global warming continues. Such reductions have been both predicted by all GCMs and observed in the field. Similar reductions in wind potential should occur in other higher latitude regions such as Western Europe, which together have most of the global wind potential [38].

5.4. Solar energy

Solar energy potential will be mainly affected by changes in cloud cover, which will affect STEC and any focused PV systems. Non-concentrating systems (most present PV systems) can use diffuse insolation, as can flat plate collectors. Using a multi-model ensemble, Patt and colleagues [84] found that at latitudes higher than about 50° N and 50° S, cloud cover would rise by up to a few percent. But between 50° N and 50° S, where almost all STEC systems can be expected to be built, cloudiness was modelled to remain the same or even decrease by a few percent. They also found

that for most PV types, performance decreases with rising temperatures. They suggest either using less heat-sensitive PV types in high temperature regions, or using STEC instead.

Geoengineering with aerosols would also lower solar energy as well as global hydropower potential. Sulphate aerosols in the lower stratosphere will tend to scatter direct light, and so will adversely affect output from existing or planned STEC systems. According to Murphy [85], 'each 1% reduction in total sunlight reaching the earth from enhancement of stratospheric aerosols will cause a 4–10% loss in output from concentrated solar power applications depending on what measure is used for electrical output'. After the Mount Pinatubo eruption in 1991, which put millions of tonnes of sulphate aerosols into the stratosphere, output of US STEC systems was significantly reduced [85]. Some passive solar systems would also be less effective. In summary, climate change may reduce PV potential but will benefit global solar potential for STEC—unless aerosol geoengineering is attempted.

5.5. Discussion

Climate change has the potential to directly affect the technical potential of all RE sources, except tidal and geothermal energy. In addition, geoengineering aerosol with aerosols could reduce the technical potential for concentrated solar, and because of reduced precipitation, hydro and even biomass potentials. The potential reduction in total RE potential is most uncertain, but its existence adds urgency to the shift to renewables; the longer we delay, the lower their technical potential. Unfortunately, since the majority input energy costs for RE must usually be made before any energy is produced, possible growth rates for RE are subject to limits [39,69]. It is thus important to reduce total energy use [86].

RE sources are not the only energy sources potentially affected by climate change. Droughts are already reducing the output of water-cooled thermal power stations, whether fossil-fuelled or nuclear plants [14]. Since climate change is expected to increase the severity of prolonged droughts, output restrictions on existing plants could increase in severity. Increased temperatures also lower power plant efficiency. Mima and Criqui [70] found only small reductions by 2050, but 8% reductions by 2100. Risk of flooding can lead to power station closures for safety reasons, and again, increased flood severity can be expected as climate changes.

6. Conclusions

By 2050, the world may need 1000 EJ of primary energy, if business-as-usual projections of global economic growth are to be realised. Given the problems facing both fossil and nuclear fuels, within a very few decades, RE will have to account for most energy production. Yet pervasive uncertainty surrounds estimates of technical potential for all renewable energy sources except hydro, both at the national and global levels. Global estimates in the published literature can vary by up to two orders of magnitude, making their use problematic for energy planning.

One explanation for the wide range of estimates for RE potential is that energy ratios are not usually factored in. We argue here that for each RE source, the energy ratio will decline as the higher-quality resources are progressively exploited, until the energy return on input energy is too small to be viable. We provide a quantitative example in the case of global wind energy. Further, since for large RE output, most will have to come from intermittent wind and solar energy, energy conversion and storage will need to be progressively implemented in the world's grids, further lowering energy ratios. When energy input is factored in, it is likely a peak in net output energy will occur, giving rise to an optimum value in annual gross RE; beyond this value, net output from RE sources will fall.

All energy sources generate unwanted environmental side-effects such as local air, water or soil pollution, greenhouse gas emissions, or biodiversity loss. Even the types of environmental damages caused by RE sources can be uncertain, mainly because of their present low levels of output compared with that needed. Siting of new RE projects have met with local environmental opposition, which could escalate as RE output is scaled up many-fold. On the other hand, their adverse environmental effects must be compared with those from fossil or nuclear energy production, which are set to rise per unit of output as more use of unconventional fossil fuels, or recourse to fast reactors, is needed.

The technical potential for solar RE, both direct and indirect, will vary with on-going climate change. For hydro, with its long project life, future uncertainty in stream flows could discourage investment. Biomass will be disproportionately affected by changes in precipitation and soil moisture levels, as well as any possible rises in extreme weather events and insect pest or fire outbreaks, because of its probable status as a residual biomass use. Global wind energy potential will fall if temperature differentials between equatorial and polar regions continue to fall. Concentrating solar energy systems such as STEC plants will experience declining output if aerosol geoengineering is implemented.

RE will have to dominate the future global energy mix, but it will not be immune to problems. Overall energy reductions, as well as RE, will be needed to minimise adverse impacts that are inevitable with any energy source. It is therefore likely that environmental and climate change constraints will act to further reduce the optimum level of gross output from RE sources below that indicated by considering direct energy inputs alone.

References

[1] BP. BP Statistical Review of World Energy 2010. London: BP; 2010.
[2] BP. BP Energy Outlook 2030. London: BP; 2011.
[3] Shell International BV. Shell energy scenarios to 2050. The Hague, NL: Shell International BV; 2008.
[4] Energy Information Administration (EIA). International energy outlook 2010. Washington, DC: US Department of Energy; 2010.
[5] European Commission (EC). World Energy Technology Outlook-*WETO* H_2. Directorate General for Research: EUR 22038. Brussels, Belgium: EC; 2006.
[6] International Energy Agency (IEA). Key world energy statistics 2010. Paris: IEA/OECD; 2010 [also earlier editions].
[7] International Atomic Energy Agency (IAEA). Energy, electricity and nuclear power estimates for the period up to 2030. IAEA-RDS-1/29. Vienna: IAEA; 2009.
[8] Riahi K, Grubler A, Nakicenovic N. Scenarios of long-term socio-economic and environmental development under climate stabilization. Technol Forecast Soc Change 2007;74:887–935.
[9] Schiffer H-W. WEC energy policy scenarios to 2050. Energy Policy 2008;36(7):2464–70.
[10] Raskin PD, Electris C, Rosen RA. The century ahead: searching for sustainability. Sustainability 2010;2:2626–51.
[11] United Nations (UN). World Population Prospects, the 2008 Revision; 2008. http://esa.un.org/unpp/ [accessed 22.02.11].
[12] Spreng D. Distribution of energy consumption and the 2000W/capita target. Energy Policy 2005;33:1905–11.
[13] Moriarty P, Honnery D. Hydrogen's role in an uncertain energy future. Int J Hydrogen Energy 2009;34:31–9.
[14] Moriarty P, Honnery D. Rise and Fall of the Carbon Civilisation. London: Springer; 2010.
[15] Association for the Study of Peak Oil and Gas (ASPO). ASPO Newsletter 100; 2009 [also earlier newsletters]. www.peakoil.net [accessed 29.04.09].
[16] Patzek TW, Croft GD. A global coal production forecast with multi-Hubbert cycle analysis. Energy 2010;35:3109–22.
[17] Heinberg R, Fridley D. The end of cheap coal. Nature 2010;468:367–9.
[18] Sims REH, Schock RN, Adegbululgbe A, Fenhann J, Konstantinaviciute I, Moomaw W, et al. Energy supply. In: Metz B, Davidson OR, Bosch PR, Dave R, Meyer LA, editors. Climate change 2007: mitigation. Cambridge, UK: CUP; 2007. p. 251–322.
[19] Hansen J, Sato M, Kharecha P, Beerling D, Berner R, Masson-Delmotte V, et al. Target atmospheric CO2: where should humanity aim? Open Atmos Sci J 2008;2:217–31.
[20] Rockström J, Steffen W, Noone K, Persson A, Chapin FS, Lambin EF, et al. A safe operating space for humanity. Nature 2009;461:472–5.

[21] Wikipedia, Fukushima I nuclear accidents. Available at: http://en.wikipedia.org/wiki/Fukushima_I_nuclear_accidents [accessed 15.05.11].
[22] Anon, Japan Scraps Nuclear Plan, Science 332 (2011) 773.
[23] Hoogwijk M, de Vries B, Turkenburg W. Assessment of the global and regional geographical, technical and economic potential of onshore wind energy. Energy Econ 2004;26(5):889–919.
[24] de Vries BJM, van Vuuren DP, Hoogwijk MM. Renewable energy sources: their potential for the first-half of the 21st century at a global level: an integrated approach. Energy Policy 2007;35:2590–610.
[25] Hafele W. Energy in a finite world: a global systems analysis. Cambridge, MA: Ballinger; 1981.
[26] Lightfoot HD, Green C. An assessment of IPCC Working Group 111 findings in Climate Change 2001: mitigation of the potential contribution of renewable energies to atmospheric carbon dioxide stabilization. Centre for Climate and Global Change Research (C^2GCR) C^2GCR Report No. 2002–5, 2002.
[27] Gross R, Leach M, Bauen A. Progress in renewable energy. Environ Int 2003;29:105–22.
[28] Field CB, Campbell JE, Lobell DB. Biomass energy: the scale of the potential resource. Trends Ecol Evol 2008;23(2):65–72.
[29] Resch G, Held A, Faber T, Panzer C, Toro F, Haas R. Potentials and prospects for renewable energies at global scale. Energy Policy 2008;36:4048–56.
[30] Klimenko VV, Tereshin AG, Mikushina OV. Global energy and climate of the planet in the XXI century in the context of historical trends. Russ J Gen Chem 2009;79(11):2469–76.
[31] Cho A. Energy's tricky tradeoffs. Science 2010;329:786–7.
[32] Tomabechi K. Energy resources in the future. Energies 2010;3:686–95, doi:10.3390/en3040686.
[33] World Energy Council (WEC). 2010 survey of energy resources. London: WEC; 2010.
[34] Moriarty P, Honnery D. Renewable energy in a warming world. Int J Energy Environ Econ 2009;16(4):343–69.
[35] Crawford R. Life cycle energy and greenhouse emissions analysis of wind turbines and the effect of size on energy yield. Renew Sustain Energy Rev 2009;13:2653–60.
[36] Zhai P, Williams ED. Dynamic hybrid Life Cycle Assessment of energy and carbon of multicrystalline silicon photovoltaic systems. Environ Sci Technol 2010;44:7950–5.
[37] Lenzen M, Munksgaard J. Energy and CO2 life-cycle analyses of wind turbines – review and applications. Renew Energy 2002;26:339–62.
[38] Honnery D, Moriarty P. Estimating global hydrogen production from wind. Int J Hydrogen Energy 2009;34:727–36.
[39] Honnery D, Moriarty P. Energy availability problems with rapid deployment of wind-hydrogen systems. Int J Hydrogen Energy 2011;36:3283–9.
[40] Herendeen RA, Plant RL. Energy analysis of four geothermal technologies. Energy 1981;6:73–82.
[41] Moriarty P, Honnery D. Liquid fuels from woody biomass. Int J Global Energy Issues 2007;27(2):103–14.
[42] Baines JT. Resources, reserves and their economic potential or how scarce is scarce? Technol Forecast Soc Change 1987;32:295–310.
[43] Pritchard S. Overloaded. Int Water Power Dam Construct 2002;54(7):18–22.
[44] Evans A, Strezov V, Evans TJ. Assessment of sustainability indicators for renewable energy technologies. Renew Sustain Energy Rev 2009;13:1082–8.
[45] Pearce F. Sunshine superpower. New Sci 2009;24(October):38–41.
[46] Moriarty P, Honnery D. Is there an optimum level for renewable energy? Energy Policy 2011;39:2748–53.
[47] Yeh S, Rubin ES. Uncertainties in technology experience curves for energy-economic models; 2010. Available at: http://steps.ucdavis.edu/People/slyeh/syeh-resources/Yeh-Rubin_Uncertainties%20in%20Experience%20Curves_18May2010-1.pdf [accessed 19.05.11].
[48] Fridley D. Nine challenges of alternative energy. Post Carbon Institute; 2010. Available at: http://www.postcarbon.org/Reader/PCReader-Fridley-Alternatives.pdf [accessed 19.05.11].
[49] Kleijn R, van der Voet E. Resource constraints in a hydrogen economy based on renewable energy sources: an exploration. Renew Sustain Energy Rev 2010;14:2784–95.
[50] Miller LM, Gans F, Kleidon A. Estimating maximum global land surface wind power extractability and associated climatic consequences. Earth Syst Dynam 2011;2(1):1–12.
[51] Moriarty P, Honnery D. What energy levels can the Earth sustain? Energy Policy 2009;37:2469–74.
[52] Abbasi SA, Abbasi N. The likely adverse environmental impacts of renewable energy sources. Appl Energy 2000;65:121–44.
[53] McCartney M. Living with dams: managing the environmental impacts. Water Policy 2009;11(Suppl 1):121–39.
[54] Boyles JG, Cryan PM, McCracken GF, Kunz TH. Economic importance of bats in agriculture. Science 2011;332:41–2.
[55] Kuvlesky Jr WP, Brennan LA, Morrison ML, Boydston KK, Ballard BM, Bryant FC. Wind energy development and wildlife conservation: challenges and opportunities. J Wildlife Manage 2007;71(8):2487–98.
[56] Simon CA. Cultural constraints on wind and solar energy in the U.S. context. Comp Technol Transfer Soc 2009;7:251–69.
[57] Dean WD. Wind turbine mechanical vibrations: potential environmental threat. Energy Environ 2008;19(2):303–7.
[58] Boehlert GW, Gill AG. Environmental and ecological effects of ocean renewable energy development: a current synthesis. Oceanography 2010;23(2):68–81.
[59] Tsoutsos T, Frantzeskaki N, Gekas V. Environmental impacts from the solar energy technologies. Energy Policy 2005;33:289–96.
[60] Saidur R, Rahim NA, Islam MR, Solangi KH. Environmental impact of wind energy. Renew Sustain Energy Rev 2011;15:2423–30.
[61] Wolsink M. Wind power implementation: the nature of public attitudes: equity and fairness instead of 'backyard motives'. Renew Sustain Energy Rev 2007;11:1188–207.
[62] Kunz TH, Arnett EB, Erickson WP, Hoar AR, Johnson GD, Larkin RP, et al. Ecological impacts of wind energy development on bats: questions, research needs and hypotheses. Front Ecol Environ 2007;5(6):315–24.
[63] Kintisch E. Out of site. Science 2010;327:788–9.
[64] Meszaros M. Lethal kickback of large scale renewable energy exploitation. AGLA Proc 2009;14(4):2–10. Available at: http://works.bepress.com/milan_meszaros/34.
[65] Pimentel D, Herz M, Glickstein M, Zimmerman M, Allen R, Becker K, et al. Renewable energy: current and potential issues. Bioscience 2002;52:1111–20.
[66] Makarieva AM, Gorshkov VG, Li B-L. Energy budget of the biosphere and civilization: rethinking environmental security of global renewable and non-renewable resources. Ecol Complex 2008;5:281–8.
[67] Fox JF, Campbell JE. Terrestrial carbon disturbance from mountaintop mining increases lifecycle emissions for clean coal. Environ Sci Technol 2010;44:2144–9.
[68] Moriarty P, Honnery D. A human needs approach to reducing atmospheric carbon. Energy Policy 2010;38(2):695–700.
[69] Moriarty P, Honnery D. The transition to renewable energy: make haste slowly. Environ Sci Technol 2011;45:2527–8.
[70] Mima S, Criqui P. Assessment of the impacts under future climate change on the energy systems with the POLES model. In: International Energy Workshop 17–19 June, Fondazione Giorgio Cini. 2009. http://halshs.archives-ouvertes.fr/docs/00/45/29/48/PDF/SM-PC_Venise.pdf.
[71] Lehner B, Czisch G, Vassolo S. The impact of global change on the hydropower potential of Europe: a model-based analysis. Energy Policy 2005;33:839–55.
[72] Hamlet AF, Lee S-Y, Mickelson KEB, Elsner MM. Effects of projected climate change on energy supply and demand in the Pacific Northwest and Washington State. Climatic Change 2010;102:103–28.
[73] Varun IK, Bhat R, Prakash. LCA of renewable energy for electricity generation—a review. Renew Sustain Energy Rev 2009;13:1067–73.
[74] Bala G, Duffy PB, Taylor KE. Impact of geoengineering schemes on the global hydrological cycle. Proc Natl Acad Sci 2008;105(22):7664–9.
[75] Zhao M, Running SW. Drought-induced reduction in global terrestrial Net Primary Production from 2000 through 2009. Science 2010;329:940–3.
[76] Heimann M, Reichstein M. Terrestrial ecosystem carbon dynamics and climate feedbacks. Nature 2008;451:289–92.
[77] Lowe JA, Huntingford C, Raper SCB, Jones CD, Liddicoat SK, Gohar LK. How difficult is it to recover from dangerous levels of global warming? Environ Res Lett 2009;4:014012 [9pp].
[78] Imhoff ML, Bounoua L, Ricketts T, Loucks C, Harriss R, Lawrence W. Global patterns in human consumption of Net Primary Production. Nature 2004;429:870–3.
[79] Erb K-H, Krausmann F, Gaube V, Gingrich S, Bondeau A, Fischer-Kowalski M, Haberl H. Analyzing the global human appropriation of net primary production—processes, trajectories, implications. An introduction. Ecological Economics 2009;69:250–9.
[80] Pryor SC, Barthelmie RJ. Climate change impacts on wind energy: a review. Renew Sustain Energy Rev 2010;14:430–7.
[81] Pereira de Lucena AF, Szklo AS, Schaeffer R, Dutra RM. The vulnerability of wind power to climate change in Brazil. Renew Energy 2010;35:904–12.
[82] Sailor DJ, Smith M, Hart M. Climate change implications for wind power resources in the Northwest United States. Renew Energy 2008;33:2393–406.
[83] Ren D. Effects of global warming on wind energy availability. J Renew Sustain Energy 2010;2:052301 [5pp].
[84] Patt A, Pfenninger S, Lilliestam J. Vulnerability of solar energy infrastructure and output to extreme events: climate change implications. In: Joint ICTP/IAEA Workshop on Vulnerability of Energy Systems to Climate Changes and Extreme Events. 2010. http://edoc.gfz-potsdam.de/pik/get/4431/0/ed1b748d3d8fbeef0b7c708634fc1b99/4431.pdf.
[85] Murphy DM. Effect of stratospheric aerosols on direct sunlight and implications for concentrating solar power. Environ Sci Technol 2009;43(8):2784–6.
[86] Trainer T. Can renewables etc. solve the greenhouse problem? The negative case. Energy Policy 2010;38:4107–14.